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Oribatid mite (Acari: Oribatida) communities reveal the negative impact of the red oak (*Quercus rubra* L.) on soil fauna in Polish commercial forests

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ABSTRACT

The red oak (*Quercus rubra* L.) is a woody plant brought to Europe from North America for its decorative value and high tolerance to frost and pollution. The species has been planted for the reclamation of brownfield sites, and introduced to commercial forests to enrich local biodiversity. Although in Poland its presence was associated with depauperation of local flora, its invasive status is still under discussion. The aim of this study was to determine the impact of red oak stands on Acari communities (Oribatida, Mesostigmata, Astigmata, Prostigmata). In the detailed analyses we focused on the Oribatida species, one of the best bioindicators of soil condition. The presence of the red oak was compared to the pedunculate (native) oak, also planted on poor acid soils. The research design included oak stands introduced in commercial forests, divided into two groups: young and old. A total number of 240 soil samples were collected, and 173 species of oribatid mites were identified. A low proportion of the Oribatida species typical for the Palearctic region, specific to deciduous forests, with sexual reproduction and belonging to the trophic level of secondary decomposers, significantly distinguished the old alien oaks from old native oaks. The results presented in this work are one of the few which concern the reaction of soil oribatid mite community to plant invasions, and provide evidence of the harmful impact of these alien tree species, which can be overlooked in short-term studies.

1. Introduction

Technological progress in the 20th century enabled people to travel between continents quickly and frequently, which has resulted in both intentional and accidental intercontinental transfer of organisms that otherwise could not have traveled that far. Although most of them could not adapt to the new environmental conditions (Hulme, 2009; Pyšek and Richardson, 2008), some did achieve reproductive success on a scale that began to threaten local ecosystems, habitats, and species. These organisms, based on COP VI/23 decision of Convention on Biological Diversity (6th Meeting of the Conference of the Parties to the Convention on Biological Diversity, Hague, Netherlands, 7–19 April 2002), are defined as invasive alien species (IAS).

Despite disputes regarding the detailed definition of invasive alien plants (IAP), it is generally agreed that these are alien plants with the ability to spread until they completely cover a new terrain (Drenovsky et al., 2012; Valéry et al., 2008). Their exceptionally rapid encroaching have been observed in areas exposed to strong anthropopression (Chytrý et al., 2009; Hulme, 2007; Tokarska-Guzik, 2005), and it currently believed that their force ultimately depends on the context of their impact, i.e. the interaction of the alien species with the indigenous ecosystem (Pyšek et al., 2012). Researchers have tried to investigate this problem by designing complementary field experiments (Maurel et al., 2013) and detailed comparisons of native and non-native species (van Kleunen et al., 2010a).

Until recently, alien woody plants were not recognized as a serious threat to native ecosystems because of the much longer development time than herbaceous plants (Pyšek et al., 2014; Richardson and Rejmánek, 2011). One significant alien species in Poland is the northern red oak (*Quercus rubra* L.), brought intentionally from Northern America in 1806 (Hereźniak, 1992). It was planted in parklands, cities and used for land restoration, thanks to its resistance to frost and pollution, great productivity and low environmental requirements (Tokarska-Guzik, 2001). Red oak was widely planted in commercial forests in the Silesian Upland, where more than 95 % of stands are exposed to the harmful impacts of industry (Kuc et al., 2012).

Considering the fact that the time from the first release of the red oak to its spontaneous spread is estimated to be 114 years (Kowarik et al., 1995), it is possible that this species is actually on the verge of initiating a process of invasion in Poland. Although some authors mention a relatively long time of presence in native forests, no cases of escape from plantations and a positive impact on local biodiversity

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Table 1
Characteristics of the 12 investigated plots with red (alien) and pedunculate (native) oak stands.

No.	symbol of the plot	species	age	[%] within the stand	GPS position	
					N (latitude)	E (longitude)
1.	YP_1	pedunculate	young	70	50º03'55,79"	18º34'24,48"
2.	YP_2	pedunculate	young	60	50º01'42,88"	18º33'41,18"
3.	YP_3	pedunculate	young	60	50º08'54,67"	18º31'59,85"
4.	YR_1	red	young	90	50º03'56,66"	18º34'08,69"
5.	YR_2	red	young	70	50º02'47,47"	18º31'33,39"
6.	YR_3	red	young	80	50º09'02,15"	18º32'29,23"
7.	OP_1	pedunculate	old	70	50º02'27,52"	18º20'11,94"
8.	OP_2	pedunculate	old	100	50º10'12,73"	18º45'11,16"
9.	OP_3	pedunculate	old	80	50º01'45,69"	18º34'10,68"
10.	OR_1	red	old	90	50º23'16,08"	19º10'58,57"
11.	OR_2	red	old	100	50º21'59,97"	19º06'36,28"
12.	OR_3	red	old	70	49º59'39,98"	18º21'58,93"

(Lasota et al., 2012), others report uncontrolled spreading, encroachment into protected areas and a harmful impact on local flora (Chmura, 2013; Ferchmin and Otręba, 2007; Woziwoda et al., 2014a). There are also works arguing that despite no clear evidence for the spontaneous formation of stands, and resulting depauperation of native flora, the surveys are short-term and focus on the traits that are easiest to observe (Danielewicz and Wiatrowska, 2014, 2012). Although the red oak is present in the NOBANIS database (European Network on Invasive Alien Species), its "invasive" status has only been recognized in Lithuania and Belgium, while for Poland it is "not known".

Soil mites are widely used in environmental monitoring, with Oribatida mites suggested as the most valuable taxon (Gulvik, 2007; van Straalen, 1998) thanks to their high diversity of life strategies (Coleman, 2008; Maraun and Scheu, 2000; Siepel, 1995). Recent studies revealed that oribatid mites can be allocated to all trophic levels of the soil ecosystem, and selected species appear to occupy a similar niches even if occur in different habitats (Maraun et al., 2011; Schneider et al., 2004). However, despite their functionality, there are only a few studies concerning the reaction of selected taxons of Oribatida or their communities to the presence of invasive plants (Belnap et al., 2005; Belnap and Phillips, 2001; Pritekel et al., 2006; Rusterholz et al., 2014; Skubała, 2012; Skubała and Mierny, 2009; St. John et al., 2006). To our best knowledge, only five studies discuss the response of Oribatida to the presence of invasive woody plants (Arroyo and Bolger, 2007; Gutiérrez-López et al., 2014; Kohyt and Skubała, 2013; Motard et al., 2015; Nicolini and Topp, 2005). None of them took account of the length of residence of the alien woody plant.

The aim of this work was to test the effect of the red oak in Polish commercial forests on the biodiversity of soil mite communities. A natural experiment was sought to analyze the research problem under conditions known to be favorable for an encroaching invasive plant: namely, the stands were planted on poor acid brown soils and the region was characterized by heavy anthropopressure. The impact of the alien red oak on soil mesofauna was evaluated by comparison to the native pedunculate oak from the same genus (*Quercus robur* L.) planted in the same soil type. In order to test the long-term invasiveness of this woody plant, the forest stands were divided into young and old age categories.

The following effects of red oak presence were assumed:

(1) lower density of soil mites, lower species richness and diversity of the mites under red oak stands compared to pedunculate oak stands,
(2) higher density of oribatid mites with broad ecological niches under red oak stands, and specialized species under pedunculate oak stands,
(3) stronger adverse impact on soil mite communities observed in the old red oak category in comparison to young red oak stands.

2. Material and methods

2.1. Study sites

The area of research was located in Upper Silesia (Southern Poland), transformed and polluted by local mining and metallurgical industries since the early 19th century. In order to eliminate geographical differences and because of a similar degree of land exploitation, the study area did not exceed 50 km radius from Katowice, the capital city of the Silesian province. In order to obtain independent examples of the responses of the oribatid mite communities, the plots were no closer than 60 m (Minor, 2011).

In order to test the effect of both the oak species and the time of their presence, and interaction of these two factors, 12 plots (10 m x 10 m) were allocated to the four categories of oak stands (i.e. young pedunculate (native) oaks, young red (alien) oaks, old pedunculate oaks, and old red oaks), representing each by three plots. The distribution of the plots within the area of research was limited by the availability of oak stands meeting the assumptions of the experiment. All plots were established within commercial forests, i.e. with the same manner of management, on low fertile acid brown soil. Young stands were 30–45 years old, and the old stands were 60–70 years old (Table 1).

2.2. Sampling and sample treatment

In the spring and autumn of 2010, 10 litter-soil samples were collected from each plot (overall 240 samples). These seasons were chosen due to the highest activity of soil fauna (Kooch et al., 2018). Samples were collected randomly by means of a steel cylinder (7.5 cm long and 4.8 cm in diameter), placed separately into plastic bags and transported to the laboratory. The soil fauna was extracted in a Tullgren apparatus and preserved in 70% ethanol. Acari were selected and successively identified as Oribatida, Mesostigmata, Prostigmata, Astigmata, with individual species identified for Oribatida. Only adult forms were determined to the species level by means of keys and original species descriptions (Niedbała, 2008; Olszanowski, 1996; Weigmann, 2006). The classification proposed by Weigmann (2006) was followed. Samples from spring and autumn, for each plot, were pooled and analyzed together.

Table 2
Dominance (D) [%] of species belonging to classes higher than subrecedent (≥ 1.1%) in at least one of analyzed categories of stands (bolded), and their allocation to ecological characteristics (geographical range, habitat, reproductive mode, trophic level). Acronymes applied on PCA diagram (Fig. 2).

No.	Species	Acronym	young oaks		old oaks		ecological characteristic			
			Pedunculate	Red	Pedunculate	Red	geographical range*	habitat†	reproductive mode‡	trophic level§
1	*Achipteria coleoptrata* (Linné, 1758)	A.col	0.6	**1.2**	0.3	0.4	holar	fo	sex	pd
2	*Berniniella conjuncta* (Strenzke, 1951)	B.con	**2.6**	**1.4**	**1.7**	**2.3**	europ	f	sex	p/s
3	*Chamobates cuspidatus* (Michael, 1884)	Ch.cus	0.1	0.3	**1.1**	0.2	holar	f	sex	sd
4	*Chamobates voigtsi* (Oudemans, 1902)	Ch.voi	**5.8**	**3.8**	**5.1**	**2.3**	palear	f	sex	sd
5	*Conchogneta dalecarlica* (Forsslund, 1947)	C.dal	**4.3**	**2.4**	0.8	0.5	palear	f	sex	unk
6	*Eniochthonius minutissimus* (Berlese, 1903)	E.min	0.0	0	**1.3**	0	cos	fo	parth	sd
7	*Hypochthonius rufulus* C. L. Koch, 1835	H.ruf	0.3	0.1	0.2	**1.1**	semicos	e	parth	p/s
8	*Metabelba pulverosa* Strenzke, 1953	M.pul	**1.8**	**1.7**	**1.7**	0.4	holar	fo	sex	sd
9	*Microppia minus* (Paoli, 1908)	M.min	**6.4**	**8.8**	**17.4**	**15.3**	cos	e	parth	p/s
10	*Microtritia minima* (Berlese, 1904)	M.mina	0.6	0.2	0.4	**4.4**	semicos	f	parth	pd
11	*Nanhermannia nana* (Nicolet, 1855)	N.nan	**2.3**	**3.3**	**2.1**	0.5	semicos	fo	parth	sd
12	*Oppiella* (*Oppiella*) *falcata* (Paoli, 1908)	O.fal	**13.9**	**11.2**	**16.3**	**1.6**	palear	df	sex	p/s
13	*Oppiella* (*Oppiella*) *nova* (Oudemans, 1902)	O.nov	**21.1**	**24.9**	**16.2**	**33.6**	cos	e	parth	p/s
14	*Oppiella* (*Rhinoppia*) *subpectinata* (Oudemans, 1900)	O.sub	**4**	**5.2**	**5**	**8.4**	holar	e	sex	p/s
15	*Oribatula tibialis* (Nicolet, 1855)	O.tib	0.3	**1.9**	0.2	0.3	holar	e	sex	sd
16	*Platynothrus peltifer* (C. L. Koch, 1839)	P.pel	0.8	**1.5**	0.3	1	semicos	e	parth	pd
17	*Punctoribates punctum* (C. L. Koch, 1839)	P.pun	0.4	0.8	**1.1**	0.8	semicos	fo	sex	unk
18	*Quadroppia michaeli* Mahunka, 1977	Q.mic	1	0.4	**1.5**	0	palear	unc	sex	unk
19	*Rhysotritia duplicata* (Grandjean, 1953)	R.dup	0.5	**1.1**	0.4	0.1	palear	e	parth	pd
20	*Steganacarus* (*Atropacarus*) *striculus* (Koch, 1835)	S.str	0.9	0.2	0.7	**1.4**	semicos	fo	parth	p/s
21	*Suctobelbella acutidens* (Forsslund, 1941)	S.acu	**1.5**	**1.4**	0.4	1	holar	fo	parth	om
22	*Suctobelbella alloenasuta* Moritz, 1971	S.all	**1.2**	0.8	0.5	0.6	holar	f	parth	om
23	*Suctobelbella hamata* Moritz, 1970	S.ham	0.2	0.1	0	**1.3**	holar	f	parth	om
24	*Suctobelbella perforata* (Strenzke, 1950)	S.per	0.5	0.7	0.8	**1.3**	palear	f	parth	om
25	*Suctobelbella sarekensis* (Forsslund, 1941)	S.sar	**2.8**	**1.6**	**1.9**	**3.1**	holar	r	parth	om
26	*Suctobelbella subcornigera* (Forsslund, 1941)	S.sub	**6.4**	**8.1**	**4.6**	**4.8**	semicos	r	parth	om
27	*Suctobelbella vera* (Moritz, 1964)	S.ver	**1.1**	0.4	0.2	0.5	palear	f	parth	om
28	*Tectocepheus minor* Berlese, 1903	T.min	**2.6**	0.5	**1.2**	0.5	semicos	df	parth	pd
29	*Tectocepheus velatus alatus* Berlese, 1913	T.ala	0.7	**1.2**	1	0.2	palear	o	parth	pd

* geographical range: europ – European; palear – Palearctic; holar – Holarctic; semicos – Semicosmopolitic; cos – Cosmopolitic.
† habitat: df – deciduous forest; f – forest; fo – forests and other; o – open; e – eurytopic; r – ruderal; unc – unclear.
‡ reproductive mode: parth – parthenogenetic; sex – sexual.
§ trophic level: sd – secondary decomposers; pd – primary decomposers; p/s – predators/scavengers; om – omnivores.

2.3. Soil mite community analyses

The density of mites in each plot sample was used to calculate the mean density within the plot.

The Shannon index of diversity (H') for oribatid mite communities were calculated by means of MVSP ver. 3.1 (Kovach, 2007). The species dominance was calculated as the ratio of individuals of the species to individuals of all species noted in the category of the oak stand. Species were assigned to six classes of dominance: superdominant > 30 %, eudominant 10.1–30 %, dominant 5.1–10 %, subdominant 2.1–5 %, recedent 1.1–2 %, subrecedent < 1 %. Species belonging to a class of dominance higher than subrecedent (≥1.1% in the community) in at least one category of stands, were allocated to the following ecological characteristics: a) geographical range: European, Palearctic, Holarctic, Semicosmopolitic, Cosmopolitic; b) habitat: deciduous forest, forest (mixed and coniferous), forest and other habitats, open environment, eurytopic, ruderal, unclear (Weigmann, 2006); c) reproductive mode (sexual, parthenogenetic) (Cianciolo and Norton, 2006; Norton and Palmer, 1991); d) trophic level: secondary decomposers, primary decomposers, predators/scavengers, omnivores, unknown, based on most recent knowledge (Maraun et al., 2011; Scheu and Falca, 2000; Schneider et al., 2005, 2004).

2.4. Statistical analysis

Two-way ANOVAs were used to test differences between oak species, oak age and the interaction of both factors (oak species x oak age) with regard to the density of mites, the number of oribatid mite species per plot and the Shannon (H') species biodiversity index. Two-way ANOVA was also applied to detect differences between the categories of stands regarding densities of species allocated to groups reflecting their ecological preferences and traits (geographical range, habitat, reproductive mode, trophic level). These analyses were applied to species belonging to a class of dominance higher than subrecedent (≥ 1.1 %) in at least one oak stand category. A Fisher LSD post hoc test was performed at $p < 0.05$. Distribution of data and homogeneity of variance was tested with Kolmogorov-Smirnov and Levene tests, respectively. Data with a non-normal distribution or heterogeneity of variance were transformed prior to analysis (see Table 3). Analyses were performed in Statistica ver. 12.0 (StatSoftInc, 2012). Principal component analysis (PCA) was used to find the factor (gradient along the ordination axis) which explained best the oribatid community composition observed in plots representing the four categories of stands. PCA analysis is recommended for a data set with a short gradient of variance, which was demonstrated by means of detrended correspondence analysis (DCA) (Lepš and Šmilauer, 2003). PCA was performed using CANOCO ver. 4.5 software (ter Braak and Šmilauer, 2002). Additional tests of the autocorrelation of plots with respect to the density of selected groups of oribatid mites were conducted using SAM ver. 4.0 (Rangel et al., 2010).

3. Results

3.1. Number, density, species richness, biodiversity

A total number of 36,518 specimens of Acari were collected containing 26,028 oribatid mites, of which 18,672 adult individuals

belonged to 173 species of Oribatida, 4531 of Mesostigmata, 3121 of Astigmata and 2838 of Prostigmata. Two way ANOVA did not reveal any statistically significant differences, for oak species, oak age or interaction of both factors in values of soil mites density (Acari in total and groups of Acari), oribatid mite density (adult forms), species richness, and biodiversity (Table S1). Despite that, in most cases, a trend of lower index values was observed under old red oaks in comparison to old pedunculate oaks. The tendency of a higher density of Astigmata was the result of a high percentage of hypopi (phoretic forms) and was noted under red oaks (Fig. S1). For young red oaks, it equals 54 %, for old red oaks: 42.3 % of all Astigmata in stand categories.

3.2. Dominance structure of oribatid mite communities

The 17 species of oribatids were identified to belong to classes from subdominant to superdominant. Dominant and superdominant species in a community were: *Oppiella* (*Oppiella*) *nova* (Oudemans, 1902), *Microppia minus* (Paoli, 1908), *Suctobelbella subcornigera* (Forsslund, 1941), *Oppiella* (*Oppiella*) *falcata* (Paoli, 1908), *Chamobates voigtsi* (Oudemans, 1902), and *Oppiella* (*Rhinoppia*) *subpectinata* (Oudemans, 1900). Among these, common to both species of oaks were: *Oppiella nova* and *Microppia minus*, *Suctobelbella subcornigera* and *Oppiella falcata*. *Oppiella falcata* was absent in higher classes of the dominance of old red oaks but eudominant for both young and for old pedunculate oaks. *Chamobates voigtsi* was noted only for pedunculate oaks stands, whilst *Oppiella subpectinata* for red oaks. Only in case of the old red oak stands the superdominant (more than 30% in the community) – *Oppiella nova* was recorded (Table 2). With regards to recedent and subrecedent classes (< 2.1% of the community), the greatest number (81 oribatid mite species) were present in the old pedunculate oak category, 74 species were noted under young pedunculate oaks and 71 species under young red oaks. Old red oaks with 65 species had the lowest number of recedents and subrecedents.

3.3. Ecological characteristics of oribatid mite communities

The 2-way ANOVA conducted for species belonging to classes higher than subrecedent (≥ 1.1%) in at least one of the oak categories (species and their ecological characteristics in Table 2), revealed statistically significant differences with regard to oak species and interaction of oak species and oak age for the density of species with Palearctic geographical range and species typical for deciduous forest habitats. For species with sexual reproduction, statistically significant differences concerned only the oak species factor and for secondary decomposers only the interaction of both factors (Table 3). The post hoc analyses showed that the density of Palearctic species, species characteristic for deciduous forests, sexual species and secondary decomposers, was lower under old red oak stands in comparison to old pedunculate oaks. Young oak stands did not differ in values of densities of these ecological groups (Fig. 1). Additionally, we conducted and found no spatial autocorrelation among all plots with respect to densities of oribatid mites showing statistically significant differences between oak stands i.e.: oribatid mites with Palearctic range (Moran's I = - 0.338, p = 0.16), these of deciduous forest habitat preferences (Moran's I = - 0.285, p = 0.28), of sexual reproductive mode (Moran's I = - 0.249, p = 0.30) and of secondary decomposers trophic niche (Moran's I = - 0.491, p = 0.06).

3.4. Oribatid mite species community composition

In indirect gradient analysis, PCA served more detailed results which revealed a gradient in oribatid mite species composition. PCA showed that the ordination of the analyzed plots in relation to the first ordination axis explains 51.7% and to the second axis 25% of the observed variability of the oribatid mite communities. In general, the first axis separated the plots into young and old stands. Only one plot of the young red oak (YR_3) was in the right part of the diagram, together with the plots of the old stands (OP_2, OP_3, OR_3, OR_1), and only two plots representing old oaks (OR_2 and OP_1) were in the left part of the diagram together with young stands. The second axis divided the plots into red and pedunculate oaks, where most of the pedunculate oaks were found in the upper part of the diagram, and the most of the red oaks in the lower part. Despite the fact that one young oak stand (YP_3) was in the lower part, and two red oak (YR_1 and YR_2) in the upper part of the diagram, they were grouped close to the first ordinate axis.

Table 3
Summary of 2-way ANOVAs conducted on mean densities of oribatid species* with regard to their allocation to geographical range, habitat, reproductive mode and trophic level. Statistical differences bolded.

	Transformation	Source of variance	F-value	p
Geographical range				
European	log (x + 100)	Oak species	0.69	0.43
		Oak age	0.07	0.8
		Interaction	0.3	0.6
Palearctic	none	**Oak species**	**16.28**	**0.004**
		Oak age	0.2	0.66
		Interaction	**7.54**	**0.02**
Holarctic	none	Oak species	0.03	0.87
		Oak age	1.22	0.3
		Interaction	0.02	0.9
Semicosmopolitic	none	Oak species	0	0.98
		Oak age	0.31	0.59
		Interaction	0.002	0.96
Cosmopolitic	none	Oak species	0.03	0.87
		Oak age	3.42	0.1
		Interaction	0.03	0.87
Habitat				
Deciduous forest	Box-Cox	**Oak species**	**22.96**	**0.001**
		Oak age	0.34	0.58
		Interaction	**11.23**	**0.01**
Forest	Box-Cox	Oak species	1.12	0.32
		Oak age	0.01	0.91
		Interaction	0.09	0.77
Forest and other	none	Oak species	2.93	0.12
		Oak age	0.53	0.49
		Interaction	4.85	0.06
Open	Box-Cox	Oak species	1.46	0.26
		Oak age	0.01	0.91
		Interaction	3.8	0.09
Eurytopic	Box-Cox	Oak species	0.3	0.6
		Oak age	4.22	0.07
		Interaction	0.27	0.62
Ruderal	none	Oak species	0.01	0.91
		Oak age	0.06	0.81
		Interaction	0.03	0.86
Reproductive mode				
Parthenogenetic	none	Oak species	0.01	0.9
		Oak age	2.54	0.15
		Interaction	0.003	0.95
Sexual	none	**Oak species**	**5.7**	**0.04**
		Oak age	0.91	0.37
		Interaction	3.42	0.1
Trophic niche				
Secondary decomposers	none	Oak species	5.56	0.05
		Oak age	0.3	0.6
		Interaction	**6.40**	**0.03**
Primary decomposers	Box-Cox	Oak species	0.02	0.89
		Oak age	0.5	0.5
		Interaction	0	0.99
Predators/Scavengers	none	Oak species	0.3	0.6
		Oak age	4.98	0.06
		Interaction	0.47	0.51
Omnivores	none	Oak species	0.001	0.98
		Oak age	0.06	0.8
		Interaction	0.01	0.9

* only species belonging to dominance classes higher than subrecedent (≥ 1.1%) in at least one of analyzed categories of stands.

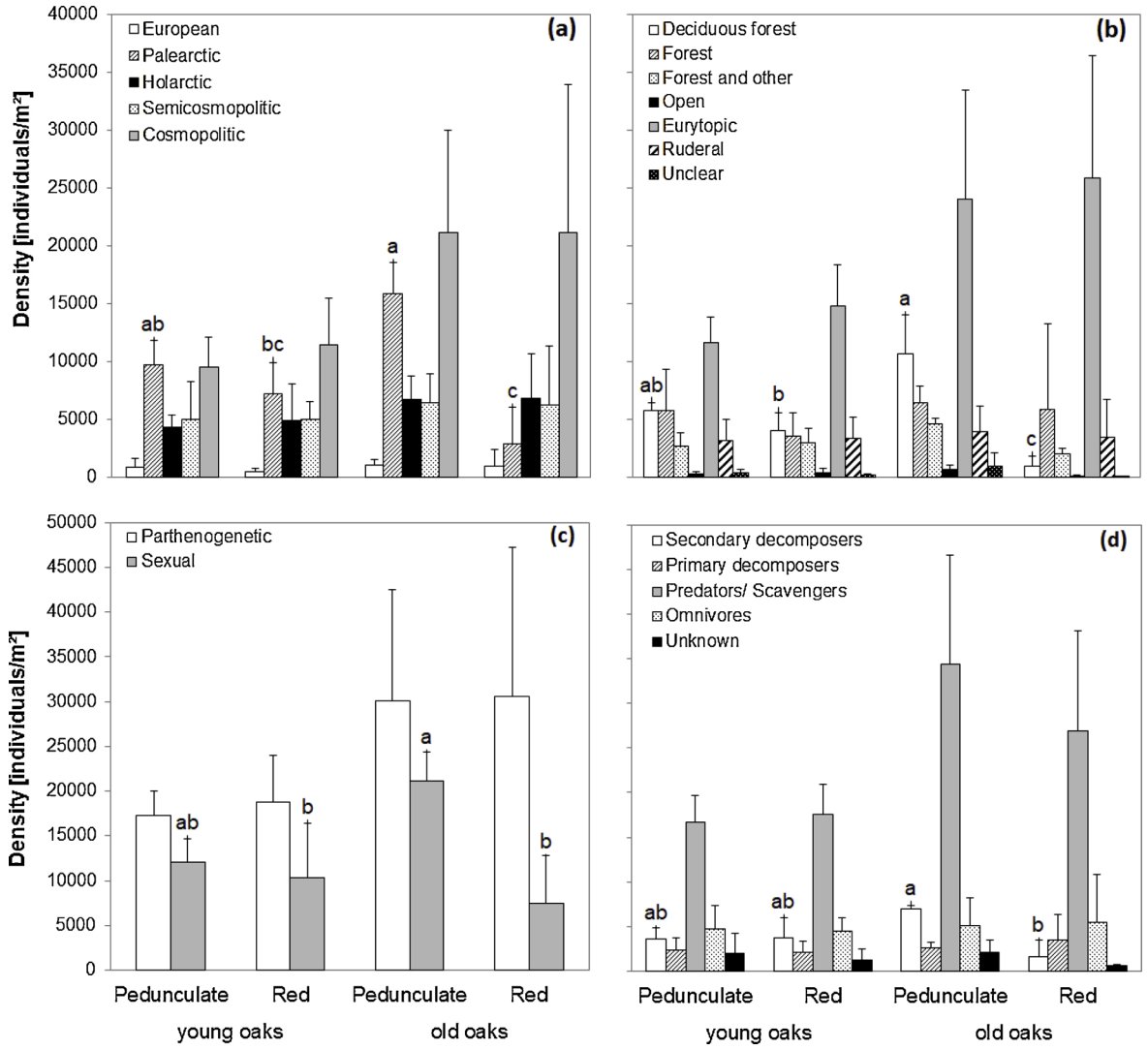

Fig. 1. Mean density + SD of oribatid mite species belonging to dominance classes higher than subrecedent (≥ 1.1%) in at least one of analyzed categories of stands with regard to their allocation to **(a)** geographical range **(b)** habitat **(c)** reproductive mode **(d)** trophic level. Statistical differences indicated by letters. Means sharing the same letters do not differ significantly ($p < 0.05$; post hoc Fisher test) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

This means that the plots with young oaks do not differ significantly in oribatid species composition and species participation. A large distance between the pair of plots representing old pedunculate oaks (OP_3 and OP_2) from a pair of old red oaks (OR_1 and OR_2) indicates great differences in oribatid mite communities.

The gradient of species composition change explains best the differences between the plots on the basis of oribatid mite ecological characteristics, mainly habitat preferences. Five young tree stands together with two old stands of both species (OP_1 and OR_2) were described by higher densities of four forest species: *Conchogneta dalecarlica* (Forsslund, 1947), *Suctobelbella vera* (Moritz, 1964), *Steganacarus* (*Atropacarus*) *striculus* (Koch, 1835), and *Punctoribates punctum* (C. L. Koch, 1839) and four eurytopic *Rhysotritia duplicata* (Grandjean, 1953), *Oppiella subpectinata*, *Oribatula tibialis* (Nicolet, 1855), *Hypochthonius rufulus* C. L. Koch, 1835. Two old stands of native oak (OP_2 and OP_3) were associated mainly with *Oppiella falcata* and *Tectocepheus minor* Berlese, 1903, i.e. species found only in deciduous forests. These plots were also characterized by higher densities of species typical or occurring in the forests *Chamobates cuspidatus* (Michael, 1884), *Metabelba pulverosa* Strenzke, 1953, *Eniochthonius minutissimus* (Berlese, 1903). With two old red oak stands (OR_1 and OR_3) eurytopic species *Oppiella nova*, *Microtritia minima* (Berlese, 1904), and *Platynothrus peltifer* (C. L. Koch, 1839) and ruderal *Suctobelbella sarekensis* (Forsslund, 1941) were related (Fig. 2).

4. Discussion

4.1. The density of soil mites, species richness, and diversity of Oribatida

Studies evaluating the condition of ecosystems by means of invertebrate bioindicators are mainly based on the measurements of densities, biodiversity and species richness of these organisms (Gulvik, 2007; Hodkinson and Jackson, 2005; McGeoch, 1998). Although in our study, the forest stands showed no statistically significant differences in the density of groups of soil mites, species richness or diversity of the oribatid mites, they were in general lower under old red oaks in comparison to old pedunculate oaks.

The higher densities of Astigmata observed under red oaks resulted from the presence of hypopi (nymphal resting stage), which indicates that this alien species created a difficult environmental condition for this group (Szymkowiak et al., 2007) and suggests possible adverse soil fauna changes in response to the prolonged presence of red oak in Polish commercial forests.

In the broad context of invasion surveys, it has been suggested that

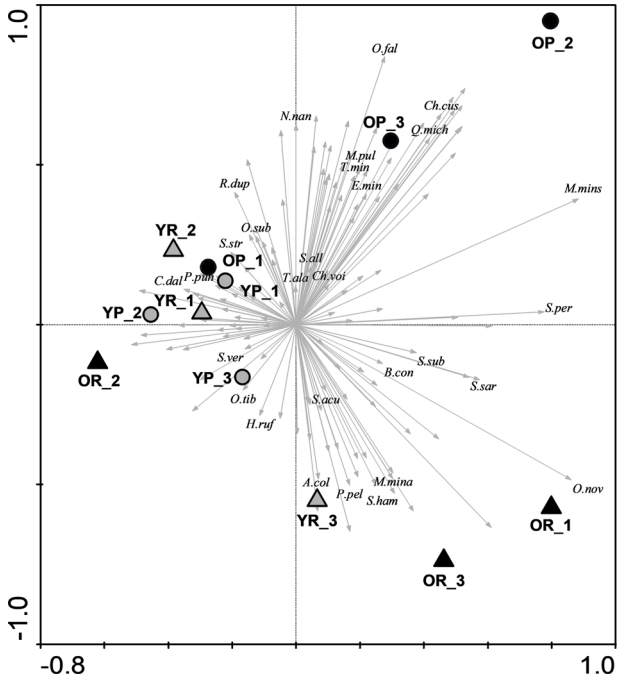

Fig. 2. Distribution of the analyzed plots of pedunculated (circles) and red oak (triangles) and oribatid species (arrows) on the ordinance diagram of the principal components analysis (PCA). Symbols of plots in Table 1, acronyms of species in Table 2. For the readability of the image, acronyms provided on figure belongs only for species belonging to classes higher than subrecedent (≥ 1.1%) in at least one of analyzed categories of stands (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the transformation rate is associated with the rate of development of the invasive alien plant and the status of the environment (Kowarik et al., 1995; van Kleunen et al., 2010b; Chytrý et al., 2009; Tokarska-Guzik, 2005; Vauramo and Setälä, 2010). Most surveys concerning non-woody invasive plants report either a decrease or no impact on the density of soil mites, species richness or diversity of analyzed taxa (Acari or lower ranks) (Belnap and Phillips, 2001; St. John et al., 2006; Sterzyńska et al., 2017; Tanner et al., 2013). In the case of non-woody invasive plants, whose growth is relatively rapid, their impact on soil fauna may be detectable quite quickly, even in natural protected areas with high biodiversity which are thought to be more resistant to invasions (Belnap et al., 2005; Pritekel et al., 2006; Skubała and Mierny, 2009). In order to observe the transformation of an ecosystem induced by invasive woody plants, researchers need to apply a much longer time scale, spanning several decades (Kowarik et al., 1995). Therefore, it can be expected that the depauperation of soil mite communities may be harder to detect using densities or biodiversity indices, especially when they are analyzed at the earlier stages of the plant development.

There are few papers reporting the impact of woody invasive plants on soil mite communities. Research on *Lonicera maackii* (Rupr.) Herder, a woody perennial shrub, an invasive plant in North America, did not show any impact on the soil mite communities (Acari group level) in a protected area (Christopher and Cameron, 2012). A study on another woody plant, *Ailanthus altissima* (Mill.) Swingle, both in a transformed terrain (Madrid, Spain) (Gutiérrez-López et al., 2014) and a forest ecosystem (France) (Motard et al., 2015), yielded results showing a clear negative impact. Motard et al. (2015) reported that for the Acari, Gutiérrez-López et al. (2014) also for Oribatida and Gamasina. Unfortunately, the aforementioned works provide no data on the age of the examined stands. Similarly to our work, Gutiérrez-López et al. (2014) observed the positive effect of *Ailanthus altissima* on the densities of Actinedida (compared to native *Populus nigra* L.). However, those authors did not provide information about Actinedida forms (active or phoretic) and discussed this group as unspecialized, which can adapt to the new conditions created by the invasive species.

In existing literature on the subject, there are surveys that provide arguments supporting the thesis of a faster adverse ecosystem transformation caused by invasive woody plants in poor soils on exploited and highly transformed land. Although the young stands of 17 year-old *Picea sitchensis* (Bong.) Carrière (used broadly in afforestation in Ireland) planted on wet mineral soils were characterized by great abundances of Oribatida – compared to the fauna from the native range of this conifer (North America), the richness and diversity indices were lower, and the communities showed strong dominance (Arroyo and Bolger, 2007). The very fast negative effect on oribatid mite communities was demonstrated at a post-mining land reclamation site in Germany (Nicolini and Topp, 2005). A significantly lower density of Oribatida mites was observed under 18 year-old red oak stands when the authors compared them to native sessile oak (*Quercus petraea* (Matt.) Liebl.) at the same age, planted on the same substrate layer (2–4 m thickness). The differences were observed on low fertile (clayed sand) but not on a highly fertile substrate (silty loam). In our study, in all analyzed plots, in total 173 species belonging to the Oribatida order were determined. This constitutes as much as 31.5 % of Oribatida fauna in Poland (Olszanowski et al., 1996), and is a rather surprising result due to the fact that the samples were collected in commercial forests planted on poor soils. It seems that the initial condition of the soil environment of Polish commercial forests was better than the clayed sand substrate layer researched in Germany and wet mineral soils in Ireland, and so the changes in our study may have been mitigated and slowed-down by this factor.

4.2. Species structure and functional groups of oribatid mites

Some researchers point to the fact that unification of an ecosystem does not always occur in biological invasions (Horáčková et al., 2014; Ricciardi and Cohen, 2007). Such an observation may result from the very generalized character of bioindicators, e.g. at the level of genera and not species, which are appropriate for assessing drastic changes in ecosystem and less suitable for gradual long-term changes. The group of mites investigated in our study, i.e. Oribatida, shows a predominance of saprophagous species, but also the presence of predators and scavengers, and one can reach different conclusions by applying generalized ecological characteristics of the entire group or analyzing characteristics of species.

As it was mentioned before, stands analyzed in our work were planted on poor acid brown soil, within commercial forests, and therefore with the high proportion of eurytopic and ruderal species in oribatid communities.

However, under pedunculate oaks and young red oaks, the eurytopic species were accompanied by species typical for forest habitats and the Palearctic range, both in the higher classes of dominance. In contrast, soil under old red oaks either contained only eurytopic species, or forest species in lower classes of dominance. Looking more closely in the structure of dominance one could observe that *Oppiella falcata*, a species typical for deciduous forests, was eudominant for both oak species at a young age. Comparing the old stands of oaks, a great decrease of proportion of this species in the community was noticeable for the red oak. Also, the presence under old red oaks of one superdominant – the cosmopolitan and eurytopic *O. nova* together with the lowest number of species belonging to recedents and subrecedents suggest the disturbed structure of these communities.

When analyzing species structure of oribatid communities by means of PCA we observed markedly larger differences between the older plots of oak species than those between the younger plots. The gradient of habitat preferences of oribatid mites along the first axis explained the best plot distribution on the ordination diagram. Young oaks were characterized mainly by forest and eurytopic species while old stands

were divided into those characterized by forest and deciduous forest (pedunculate oaks) and mainly eurytopic and ruderal species (red oaks). The reason for the two plots of old oaks (OR_2 and OP_1) being among the young oak stands in Fig. 2 may be a too short time interval between age categories which indicate the need to analyze stands older than 60–70 years old.

Statistically significant differences revealing an unquestionable negative impact of red oak were observed when analyzing oribatid species grouped according to their ecological characteristics (or function in the ecosystem). The division can be seen in the Table 2.

With regard to geographical range of oribatid mites, it was shown how alien the American oak was to European forests. The density of oribatid species with the Palearctic range was statistically lower under the red oaks in comparison to the pedunculate oaks (in general, when young and old were pooled together). The interaction of the oak species and oak age factors revealed that older stands of red oaks were characterized by the lower density of species with Palearctic range in comparison to the younger red oak stands. The direction of changes under the native oak stands (i.e. old vs young stands) was clearly opposite.

Our results show that with their age the red oak stands caused the oribatid community changes (old vs young stands) similar to those observed under one of the most dangerous invasive plants – the giant knotweed (*Reynoutria sachalinensis* (F. Schmidt) Nakai). In studies conducted in Poland, a greater participation of oribatid species with broad geographical range, and eurytopic species were noted on plots with invasive plants in comparison to the adjacent control sites with native flora (Skubała, 2012). Similarly, species of Holarctic or cosmopolitan distribution dominated in the oribatid and mesostigmatid mite communities under *Picea sitchensis*, the alien woody plant used for afforestation in Ireland (Arroyo and Bolger, 2007).

The reproductive mode of oribatid mite species was the third of the ecological characteristics tested. The low density of species reproducing sexually significantly distinguished the red oaks (young and old analyzed together) from the pedunculate oaks. It was also noticeable that the density of sexual species was the lowest under old red oaks. Despite the different concepts of the relationship between the reproductive mode of oribatid mite species and the quality or condition of the environment, the higher participation of parthenogenetic ones are associated primarily with difficult conditions or environmental stress, while the predominance of sexual species indicates a good state of the environment (Farská et al., 2014; Lindberg and Bengtsson, 2005; Maraun et al., 2019).

The results concerning the densities of species divided by trophic levels showed that the trophic structure of the forest ecosystem was disrupted by the prolonged presence of the red oak. Statistically significant differences for the interaction of oak species and oak age was noted for densities of secondary decomposers. Lower densities of specimens belonging to this trophic level was observed under old red oak stands compared to young stands, and the direction of changes was opposite for the native oaks. Again, the lowest density of secondary decomposers was observed under the old red oaks. Studies concerning the trophic structure of oribatid mites under red oak stands within its native range, in North America, revealed that decomposition of its litter is accelerated by the endophagous oribatid mites, feeding on litter of a low decomposition degree, in other words, primary decomposers (Hansen, 1999). Thus, probably for the complete process of decomposition, in which Oribatida are one of the key elements, the red oak may need species which evolved with it in the original range, which are absent in European forests. A similar explanation is suggested by the authors comparing species composition of mycorrhizal fungi associated with red oak in its natural range and in Poland (Trocha et al., 2012).

The condition of oribatid mite communities under stands of pedunculate and red oaks from the area of the Silesian province is in contrast with arguments about the superiority of the alien species over natives in areas exposed to industrial emissions (Kuc et al., 2012). Due to the danger of missing the moment of “explosion” of invasion, some researchers call the red oak a “sleeper weed” (Woziwoda et al., 2014b). According to our results, the red oak seems to play such a role in forest ecosystems.

5. Conclusions

The prolonged presence of the red oak introduced to the Polish forests seems to create unfavorable conditions for the development of soil mite communities. Although only statistically insignificant trends were observed when analyzing the density of soil mites, and the richness and species diversity of Oribatida, a clear negative impact from the red oak was visible while analyzing the ecological characteristics and traits of the mite populations. The old red oak stands seem to lead to a degeneration of oribatid mite communities, manifested in the elimination of species which prefer forest microhabitats, and also in the trophic structure disorder visible from the low density of secondary decomposers participating in the final stages of litter decomposition. Harsh environmental conditions under the old red oak stands are indirectly indicated by a statistically significantly lower proportion of species with a sexual mode of reproduction.

These results provide first evidence of the negative impact of the red oak on oribatid mite communities in Polish commercial forests and indicate the need for long-term studies on other alien woody plant species.

We declare no conflict of interest

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pedobi.2019.150594.

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